

Everpresent Lambda:

(astro-ph/0209274)

“Why Now?”

&

Quantum Cosmology

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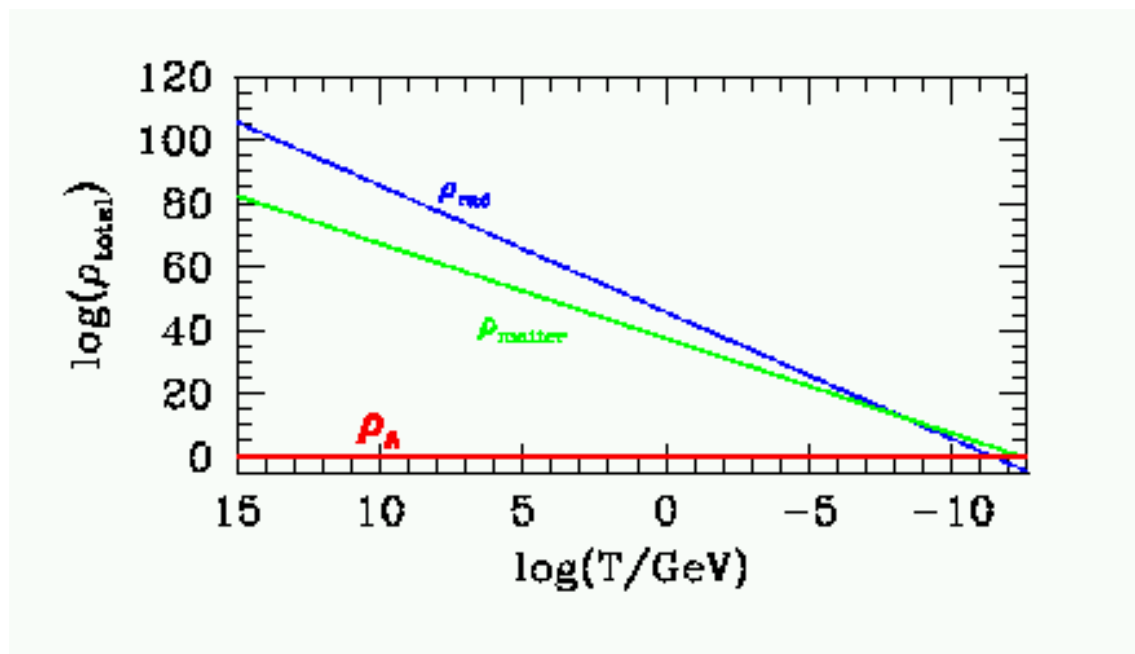
(with: S. Dodelson (FNAL), R. Sorkin & M. Ahmed (Syr. NY)

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## Two Cosmological Constant Problems:

I. *Naturalness: Why is  $\Lambda \ll M_p^4$ ?*

II. *Cosmic Coincidence: Why Now?*



*Solution:  $\Lambda$  is Always Important!*

Sorkin's Conjecture (1987):  $\Lambda$  fluctuates and is  $O(H^2)$  at every epoch.

This is not compatible with standard GR. His conjecture follows from two aspects of causal set theory: Discrete analogs of Lorentzian manifolds and Unimodular Quantum Gravity.

## *Causal Set Theory*

- Causal sets ( “causets” ) combine notions of *discreteness* and *order* to form a structure on which to found quantum gravity.
- A Lorentzian manifold can be constructed from causal ordering (light-cones) and volume measure  $d^4x\sqrt{-g}$ .  $\rightarrow$  causets are a discrete analog.
- A Lorentzian manifold corresponds to a certain class of causets. A causet can be constructed from a given manifold through “Poisson sprinkling” .

## *Unimodular Gravity (UG)*

Vary the Einstein-Hilbert action

$$\frac{1}{2} \int d^4x \sqrt{-g} R \quad (1)$$

subject to the constraint that  $\sqrt{-g} = 1$ .

Implement by introducing a Lagrange multiplier term

$$\int d^4x \sqrt{-g} \Lambda \equiv \Lambda \mathcal{V} \quad (2)$$

and making arbitrary variations of the metric.

UG is classically equivalent to GR. Quantum mechanically, however, they are very different.

$$\text{W-D: } H\Psi = 0$$

$$\text{S-U: } H\Psi = i\partial_\gamma \Psi$$

GR gives the Wheeler-deWitt eqn. UG gives the Sorkin-Unruh eqn.

## $\Lambda$ *Fluctuations*

We expect an “Energy-Time” uncertainty relation of the form:

$$\Delta\Lambda \sim \frac{1}{\Delta\mathcal{V}} \quad (3)$$

From “Poison Sprinkling” in Causal Set Theory, we expect

$$\Delta\mathcal{V} \sim \sqrt{\mathcal{V}} \sim H^{-2} \quad (4)$$

where we identify  $\mathcal{V}$  with the four-volume of the past light-cone.

This is exactly what is needed!

## *How to Implement?*

Causal set dynamics is incomplete. (Here we have discussed things at the level of kinematics.) We will implement a fluctuating cosmological term phenomenologically.

- Discretize “Time”  $\mathcal{V}$ , the four-volume of the backward light-cone.
- Evolve the scale factor and matter energy densities according to the Friedmann equation and first law.
- Evolve  $\Lambda$  stochastically.

Details:

$\Lambda$  update equation:

$$\Lambda_{i+1} = \Lambda_i + \frac{\alpha}{\mathcal{V}_i} \xi_i \sqrt{d\mathcal{V}} \quad (5)$$

where the  $\xi_i$  are Gaussian random variables with zero mean and unit variance.

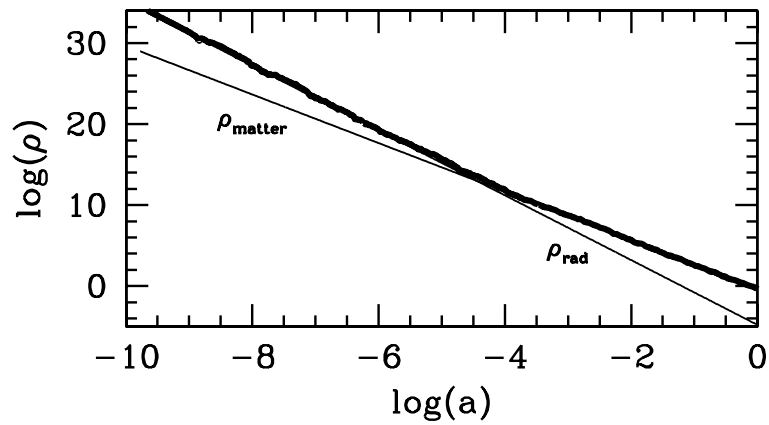
Four-volume:

$$\mathcal{V}(t) = \frac{4}{3}\pi \int_0^t dt' a^3(t') \left[ \int_{t'}^t \frac{dt''}{a(t'')} \right]^3 \quad (6)$$

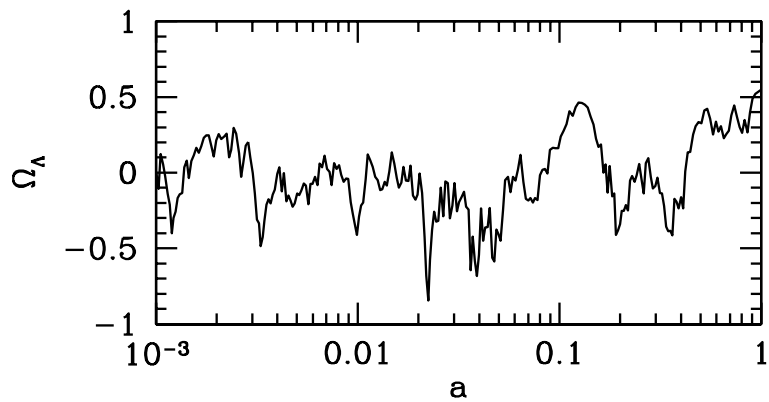
Technical note: much simpler in conformal time. There exists a simple 4-th order equation for  $\mathcal{V}(\eta)$ .



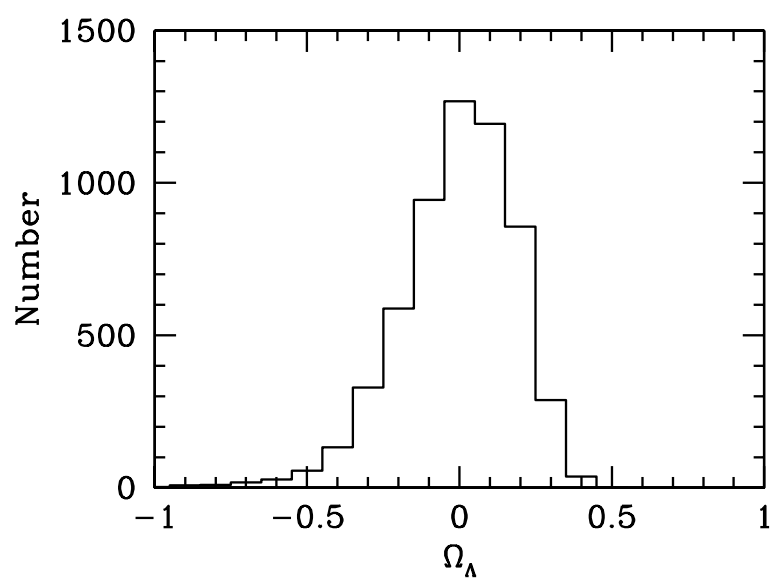
*It Can Work!*



- $\Omega_\Lambda$  tracks the dominant contribution.
- $\Omega_\Lambda$  can be small (or negative) during BBN.
- $\Omega_\Lambda$  can be significant today.



*Histogram of  $\Omega_\Lambda$  for 6000 runs*



*$\alpha = 0.01$*

## *Conclusion*

Sorkin's Conjecture seems to be viable, at least with this implementation.

but still some (many) issues:

- How probable is a successful cosmology?  
Can we survive CMB and LSS constraints?
- How do we deal with  $\rho_{\text{tot}} \rightarrow 0$ ?  
Collapse? Tunneling?
- What about inflation? Homogeneity?
- Why is  $\langle \Lambda \rangle = 0$ ? Still have the C.C. problem.